

Sensitive Skin for Biologically Inspired Aerospace Materials and Structural Elements Based on Nanotechnology

Michael S. Shur

Center for Integrated Electronics, ECSE, and Physics
Rensselaer Polytechnic Institute, Troy, N Y USA

This presentation is available on the WEB at
http://nina.ecse.rpi.edu/shur/NASA_ICASE_Workshop.htm/

Collaborators: J. Dordick, P. Ajayan, S. Wagner, J. C. Sturm,
T. Borca-Tasciuc, John Wen, Linda Schadler, R. Siegel



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Talk Outline

- Biologically inspired sensitive skin concept
- Emerging enabling technologies
 - Nanotube composites
 - Large area device arrays on flexible substrates
 - Biocomposites
 - THz detection of hazardous biological and chemical agents
- Conclusion



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Sensitive Skin: http://nina.ecse.rpi.edu/sensitive_skin

“Sensitive skin” –

large area sensor and detector array
fabricated on flexible stretchable substrate

- Applications

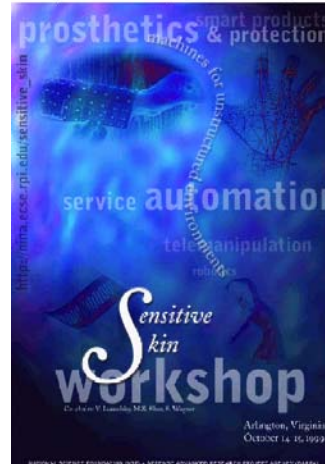
- Robots operating in unstructured environment
- Medicine and biology
- Artificial skin,
- Prosthetics
- Biomedical tests
- Physiotherapy
- Industrial controls
- Consumer electronics



Rensselaer

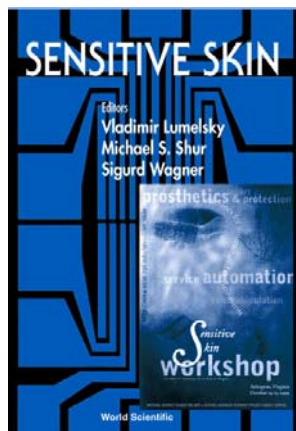
<http://nina.ecse.rpi.edu/shur/>

See Workshop report at
http://nina.ecse.rpi.edu/sensitive_skin



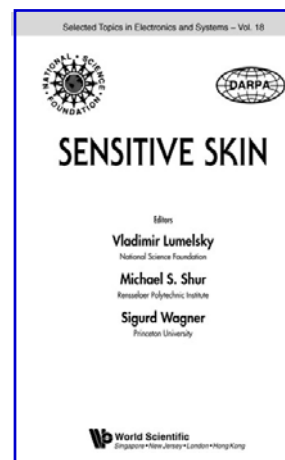
shurm@rpi.edu

Workshop Proceedings



Rensselaer

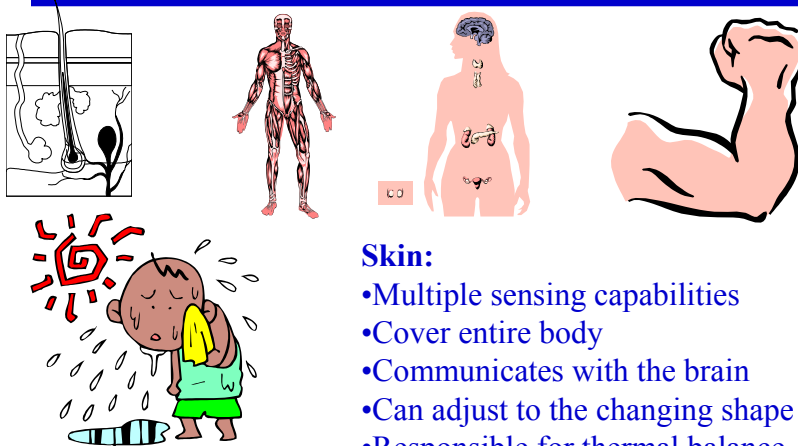
<http://nina.ecse.rpi.edu/shur/>



World Scientific
Singapore • New Jersey • London • Hong Kong

shurm@rpi.edu

Biological inspiration for Novel Structural Spacecraft/Aircraft Elements: Skin, brain, and skeleton



Skin:

- Multiple sensing capabilities
- Cover entire body
- Communicates with the brain
- Can adjust to the changing shape
- Responsible for thermal balance
- Self-cleaning/self-healing



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Suit Talking on the Phone (After “**Master and Margarita**” by M. Bulgakov)

In the famous Russian novel *Master and Margarita* by Mikhail Bulgakov, one of the characters, a high-level Moscow bureaucrat, offends the Devil. For a swift and terrible punishment, he is banished from his suit, but his suit continues to sit at his desk, signing papers, barking commands, and generally functioning in the same way as its former wearer. This talking suit evokes the image of sensing and acting cloth -- a bendable, stretchable skin with intelligent processing capabilities. Present-day electronics technology does not yet allow us to produce such sensitive skin.

But the progress toward this goal has already started!



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Prototype sensitive skin applications Ballerina dancing with a robot manipulator (movie frame)



Sensitive skin module: $8 \times 8 = 64$ infra-red sensor pairs (LEDs and detectors); the distance between neighboring pairs 25 mm
surface mounting technology; Kapton substrate.
(After Vladimir Lumelsky, University of Wisconsin-Madison).



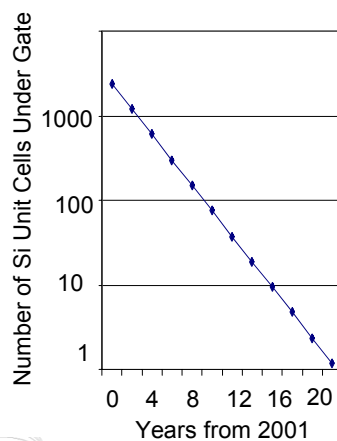
After Vladimir Lumelsky, Robotics Laboratory, University of Wisconsin-Madison.

Rensselaer

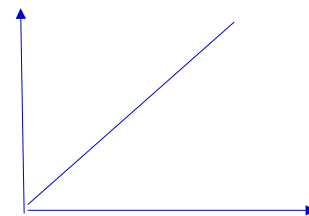
<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Inverse Moore Law



Maximum VLSI circuit size



Semiconductor device
Integrated circuit
Giant area electronics
Flexible substrates
Sensitive skin



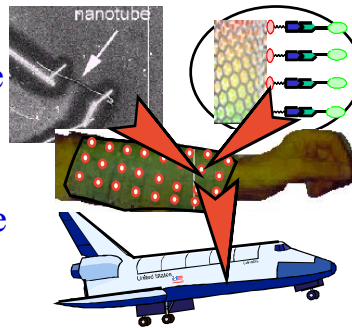
Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Sensitive Skin Concept for Spacecraft/Aircraft

- Structural elements using nanocomposites
- Sensitive skin cover with multiple sensing capabilities including detection of hazardous agents
- Actuation arrays for shape/surface control
- Self-healing, self-cleaning capabilities



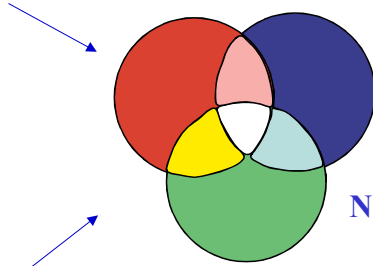
Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Approach: Sensitive Skin/Bio Based Materials/Nanocomposites

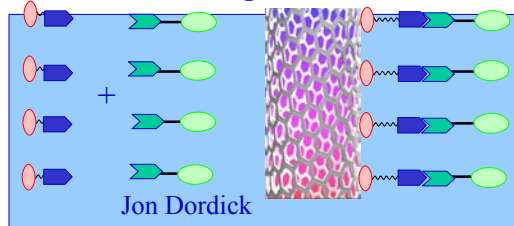
**Bio-inspired nanostructure
sensitive skin sensor arrays**



Biologically based materials

*Example:
Exploiting Enzymes for Structured
Polymer Growth and Membrane
Applications on Nanotubes*

Nanostructured composite materials



Rensselaer

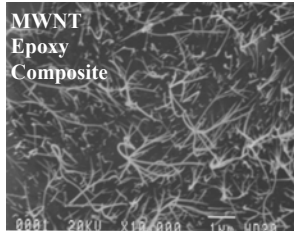
<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

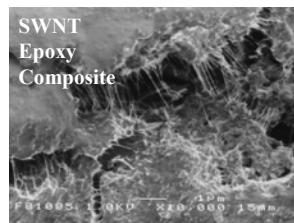
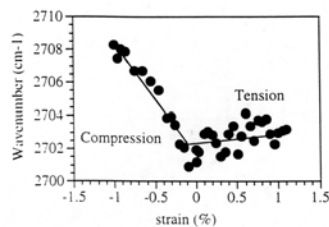
Nanotube Composites for Structural Elements: Recipe for Strength/Light Weight

Light Weight, High Strength
High Conductivity
Novel Properties (e.g. Optical)

Polymer-Nanotube Interactions
Load Transfer
Dispersion/Microstructure



Raman Data
on Load Transfer
in MWNT-Epoxy



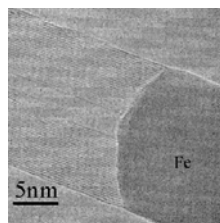
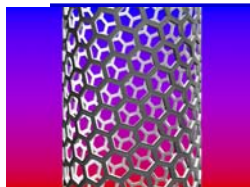
Rensselaer

Linda Schadler, P. Ajayan, R. Siegel

<http://nina.ecse.rpi.edu/shur/>

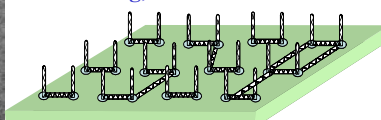
shurm@rpi.edu

Carbon Nanotubes Research @ RPI: Overview



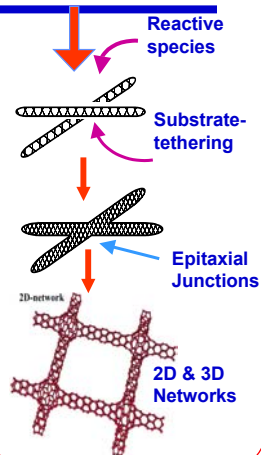
Nanotube-Nanowire Junctions

Growing 2-D, 3-D Architecture
Building Junctions, Networks
Sizing, Structure Selection
Chemistry, Functionalization
Nanotube Polymer Composites
Tough Multilayer Composites
Nanomechanical Behavior
Electrical, Thermal Transport
Nanotube Sensors
Modeling, Simulations



Nanotube-Networks

FIB, e⁻ beam welding



Rensselaer

Ajayan

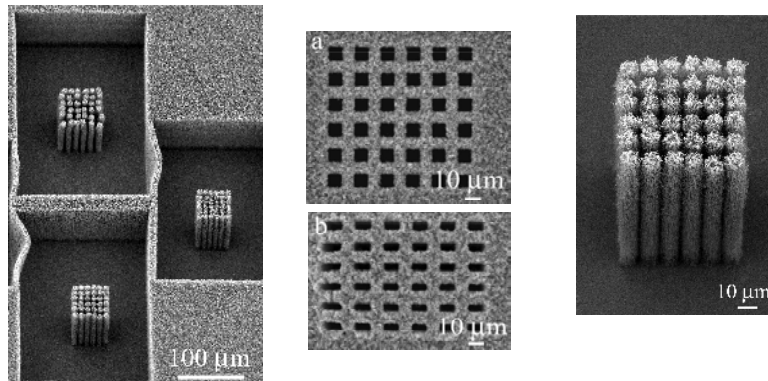
Ajayan et al.

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Controlled Assembly of Carbon

Nanotube Architectures



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

Ajayan et al.

shurm@rpi.edu

Nanotube Composites: Possible Applications

- High Strength Composites**
- High Toughness Composites (e.g. Ballistic Protection)**
- High Conductivity Plastics**
- Optically Active Filled Polymers**
- Composites for Shielding (EMI) Applications**
- Filled Plastics for Bio-medical Uses**
- Adhesive Plastics**
- Strain Sensors**
- Plastics for High Tolerances (Dimensional Stability, Surface Finish)**
- High/Medium Temperature Metal/Ceramic Matrix Composites**



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

Schadler, Ajayan et al.

shurm@rpi.edu

Technological Challenges

Materials:

Low temperature deposition
Flexible stretchable
substrate
Flexible/stretchable metals
Transparent metals
Heterostructures
Ultra large area processing
Continuous material
deposition

Device Building Blocks

Ohmic Contacts flexible,
stretchable
P-n junctions
MIS structures
Heterostructure diodes
Stability
Processing on flexible
substrates and/or threads and
cloth

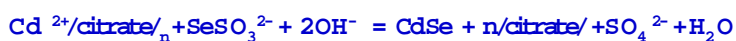


Rensselaer

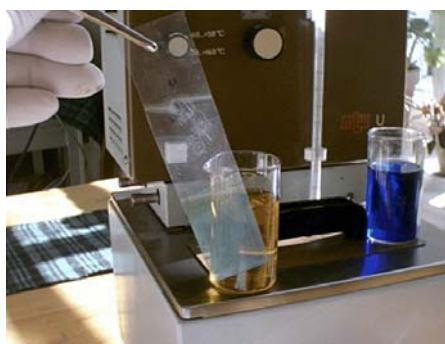
<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Chemical reaction for deposition of polycrystalline CdSe films



- Special surface treatment
- Special sensitizing process



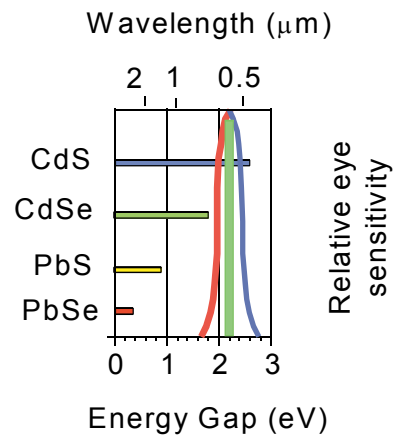
Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Semiconductor materials for sensitive skin

CdS (2.4 eV)
CdSe (1.75 eV)
PbS (0.4 eV)
PbSe (0.24 eV)
Cu_xS metal



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

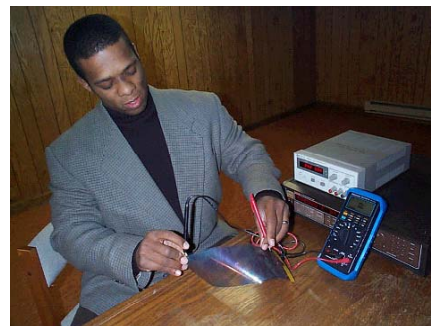
shurm@rpi.edu

Large Areas Can Be Covered

CdS on viewfoil



Cu_xS on viewfoil



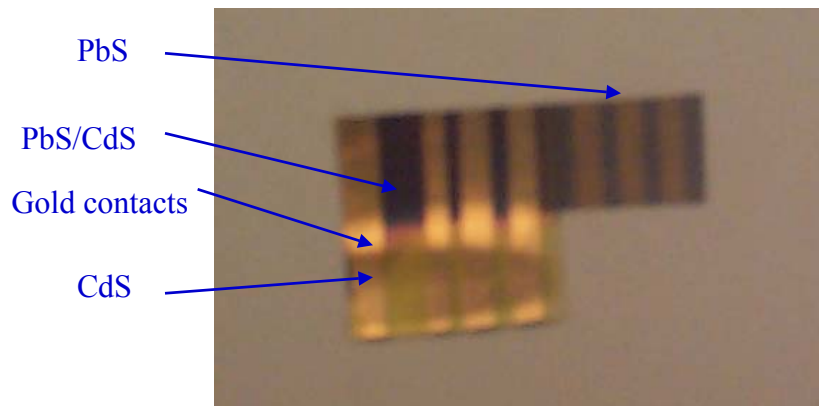
Rensselaer

<http://nina.ecse.rpi.edu/shur/>

Courtesy BITs, Inc.

shurm@rpi.edu

CdS/PbS heterostructure with contacts

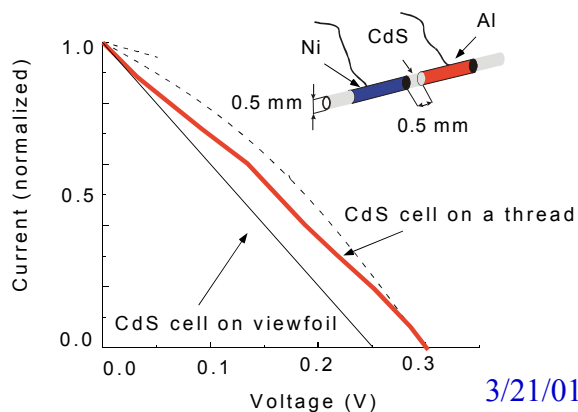


Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Solar Cells on Viewfoils and Threads For electotextiles and sensitive skin applications



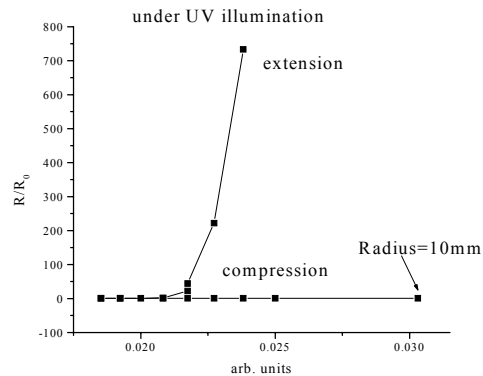
Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Nanocrystals on Flexible Stretchable Substrates for Sensitive Skin Applications

1 nm



Nanometer size crystallites in a CdS film deposited on view foil.

One can distinguish individual atoms. Notice huge reproducible change in resistance under tension

Courtesy of BITs, Inc.



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

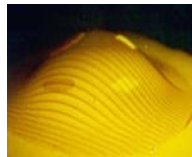
shurm@rpi.edu

Electronics for curved and draped surfaces Sigurd Wagner and James C. Sturm, Princeton University



Electronic paper from E Ink

is based on an active matrix of amorphous silicon thin film transistor on a flexible steel foil backplane, invented and made at Princeton



Spherically shaped circuit of silicon islands

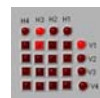
uses novel processes for making electronics on deformed surfaces, and employs a new approach to interconnecting circuits on non-developable surfaces



Touch sensor matrix

provides localized sensing on drapeable fabric

Left: pilot 4x4 matrix Right: displayed signal



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

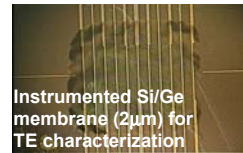
“THERMOELECTRIC SKIN”

Develop thin, flexible, high efficiency, thermoelectric devices for active heating/cooling and distributed power generation.

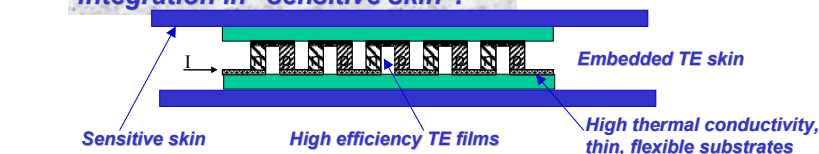
High efficiency, low-dimensional thermoelectrics (e.g. quantum dots, nanowires, superlattices).



TE device micro-fabrication and integration in “sensitive skin”.



Prof. T. Borca-Tasciuc, RPI



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Advantages of massive amount of actuators-sensors in controlling aerodynamic vehicles

- Robust, distributed vibration suppression due to sensor/actuator collocation
- Fine range of shape control
- Self diagnosis
- On-line reconfiguration
- Fault tolerance



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

John Wen

shurm@rpi.edu

Actuator/Sensor Challenges:

- Transducer constraints (displacement, dynamic range, force)
- Transducer nonlinearity (hysteresis, creep, saturation, fatigue)
- Choice of transducer location (optimal placement)
- Control algorithm for combined distributed and centralized control (information and computation distribution)
- Fault detection and mitigation algorithms
- Concurrent mechanical and control design to fully take advantage of the transducers (design for easy of control and fault recovery)

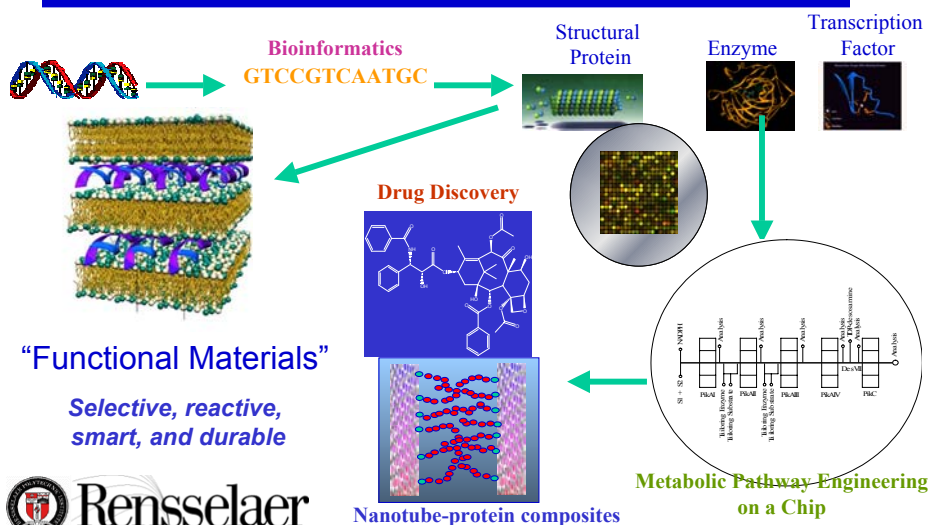


John Wen

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

*Biomolecular Engineering for Design of New
Synthetic Pathways and New Materials
(J. Dordick, P. Ajayan)*



Rensselaer

Nanotube-protein composites

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Biocatalysis for Discovery

Break the paradigm of using enzymes and metabolic pathways for “large” scale synthetic chemistry

- Bioinformatics-driven new biocatalyst discovery for enzyme and pathway manipulation
- Microscale biocatalysis
- *In vitro* metabolic pathway engineering
- Enzymes with high activity under processing conditions with tailored selectivity
- Metabolic pathways that can be discovered, manipulated, and improved
- Discovery and improvement of small molecules that can influence complex networks and regulatory pathways



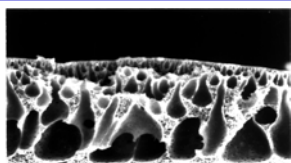
Rensselaer

Jon Dordick

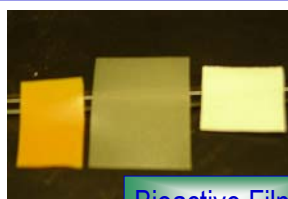
<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

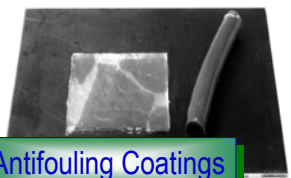
Biocatalytic Composite Materials



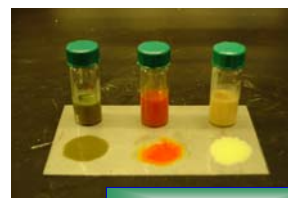
Reactive Membranes



Bioactive Films



Antifouling Coatings



Antiseptic Paints



Rensselaer

Jon Dordick

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Terahertz Detection of Biological Agents

A. G. Markelz, A. Roitberg and E. J. Heilweil

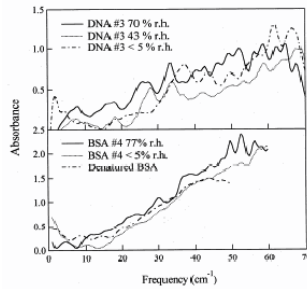


Fig.1 Different DNA samples' absorbance of THz .

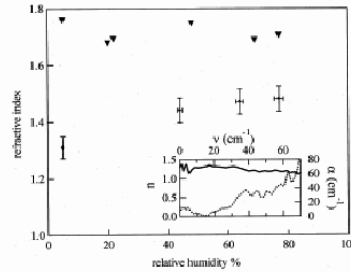


Fig.2 Refractive index of various DNA samples as function of r.h. at $\nu=25\text{cm}^{-1}$. Inset: real part and absorption spectra of sample DNA3#.



From <http://www.rensselaer.edu/~zhangxc/about/home.htm>

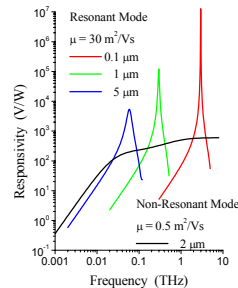
Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Detectors and Emitters: Plasma Wave Electronics

- 2D electrons in a FET may behave as a fluid
- These fluid supports plasma waves
- Plasma waves can be used for terahertz devices
- Electronic flute, detector, oscillator, mixer



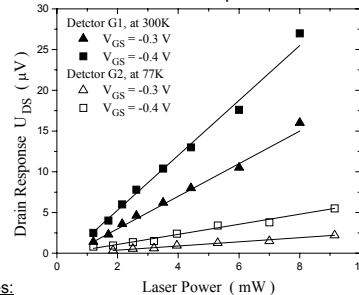
Predicted detector responsivity



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

AlGaAs/GaAs HEMT
Terahertz Detector Response



References:

- M. I. Dyakonov and M. S. Shur, Detection, Mixing, and Frequency Multiplication of Terahertz Radiation by Two Dimensional Electronic Fluid, IEEE Transactions on Electron Devices, Vol. 43, No. 3, pp. 380-387 (1996)
- M. S. Shur and M. Dyakonov, Two-Dimensional Electrons in Field Effect Transistors, International Journal of High Speed Electronics and Systems, Vol. 9, No. 1, pp. 65-99, March (1998)

<http://nina.ecse.rpi.edu/shur/PlasmaElectronics.html>

shurm@rpi.edu

Conclusions

- Sensitive skin is a new paradigm in sensing and control
- Synergy between nanocomposites, nanostructured large area flexible films, bionanocomposites and new devices concepts will lead to revolutionary changes in spacecraft and aircraft industry



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Sensitive Skin: To Probe Further

- J. Sinius, R. Gaska, and M. S. Shur, Flexible Semiconductor Films for Sensitive Skin, in Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robotics and Systems, IEEE Catalog Number :00CH37113C, ISBN: 0-781-6351-5, IEEE (2000) pp. 1511-1515
- V. Lumelsky, M. S. Shur, and S. Wagner, Editors, Sensitive Skin, World Scientific, ISBN 981-02-4369-3, 2000
- V. Lumelsky, M. S. Shur, S. Wagner, Sensitive Skin, IEEE Sensors Journal, Volume 1, No. 1, pp. 41-51 (2001)
- M. S. Shur, J. Sinius, R. Gaska, and S. Rumyantsev, Photovoltaic Effect in CdS on Flexible Substrate, Electronics Letters, vol. 37, No. 8, pp. 518-519 (2001)
- M. S. Shur, G. Gaskiene, S. Rumyantsev, R. Rimeika, R. Gaska, and J. Sinius, Photovoltaic Effect in Threads Covered with CdS, Electronics Letters, Vol. 37, No. 16, pp. 1036-1038 (2001)
- Visit: http://nina.ecse.rpi.edu/sensitive_skin/



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Nanotubes and nano composites: to probe further

- P. M. Ajayan, I.S. Iijima, Nature 361, 333 (1993).
- P. M. Ajayan and T.W. Ebbesen, Rep. Progress Phys. 60, 1025 (1997).
- S. Curran, P. M. Ajayan, W. Blau, D. L. Carroll, J. Coleman, A. Dalton, A. P. Davey and B. McCarthy, "Composite from PPV and Carbon Nanotubes: A novel material for molecular optoelectronics", Adv. Mater., 10, 1091, 1998
- L. S. Schadler, S. C. Giannaris and P. M. Ajayan, "Load Transfer in Carbon Nanotubes", Appl. Phys. Lett., 73, 3842, 1998.
- P. M. Ajayan, L. S. Schadler, C. Giannaris and A. Rubio, "Mechanical response of single walled carbon nanotubes in polymer nanocomposites", Adv. Mater., 12, 750 (2000).
- R. Czerw, Z. Guo, P. M. Ajayan, Y. Sun and D. L. Carroll, "Organization of polymers onto carbon nanotubes; route to nanoscale assembly, Nanoletters, 1, 423 (2001).
- B.Q. Wei, Z.J. Zhang, G. Ramanath, and P.M. Ajayan, Appl. Phys. Lett. 77, 2985 (2000).



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

Bio nano composites: to probe further

- Y.D. Kim, J.S. Dordick, and D.S. Clark (2001), "Siloxane-based biocatalytic films and paints: versatile coatings for producing enzymatically active surfaces", Biotechnol. Bioeng. 72, 475-482.
- J. Kim and J. S. Dordick (2001), "Biocatalytic Silicates as Active Enzyme-Inorganic Composites", Biotechnol. Bioeng. (submitted).
- J. Kim, T. J. Kosto, J. C. Manimala, E. B. Nauman, and J. S. Dordick (2001), "Preparation of Enzyme-In-Polymer Composites with High Activity and Stability", AIChE J. 47, 240-244.
- S. J. Novick and J. S. Dordick (2000), "Investigating the Effects of Polymer Chemistry on the Activity of Biocatalytic Plastic Materials", Biotechnol. Bioeng. 68, 665-671.
- X.-C. Liu and J. S. Dordick (1999), "Sugar Acrylate-Based Polymers as Chiral Molecularly Imprintable Hydrogels". J. Polym. Sci. Part A: Polym. Chem. 37, 1665-1671.



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu

To probe further: detection of hazardous biological and chemical agents

- <http://www.rpi.edu/~zhangxc>
- B. Knoll and F. Keilmann, "Mid-infrared scanning near-field optical microscope resolves 30 nm," *J. Microsc.* **194**, 512 (1999).
- F. Zenhausern, Y. Martin and H. K. Wickramasinghe, "Scanning interferometric apertureless microscopy: Optical imaging at 10 Angstrom resolution" *Science* **269** 1083 (1995).
- P.Y. Han, G.C. Cho, and X.-C. Zhang, "Time domain tansillumination of biological tissues with terahertz pulses," *Opt. Lett.*, **25**, 242 (2000)



Rensselaer

<http://nina.ecse.rpi.edu/shur/>

shurm@rpi.edu